Forecasting Tides, Storm Surges, and Their Interaction Around the North Sea Using Machine Learning

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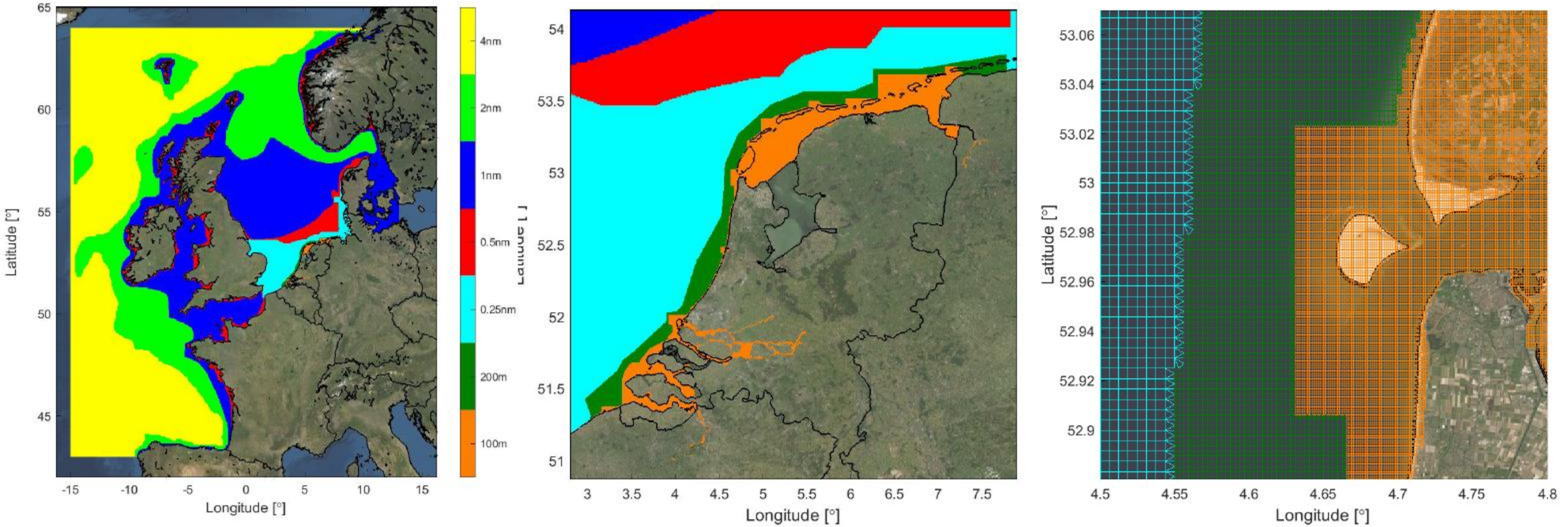
4TH INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES, AND COASTAL HAZARDS

Incorporating the 18th International Waves Workshop

UC | IH cantabria
INSTITUTO DE HIDRÁULICA AMBIENTAL
UNIVERSIDAD DE CANTABRIA

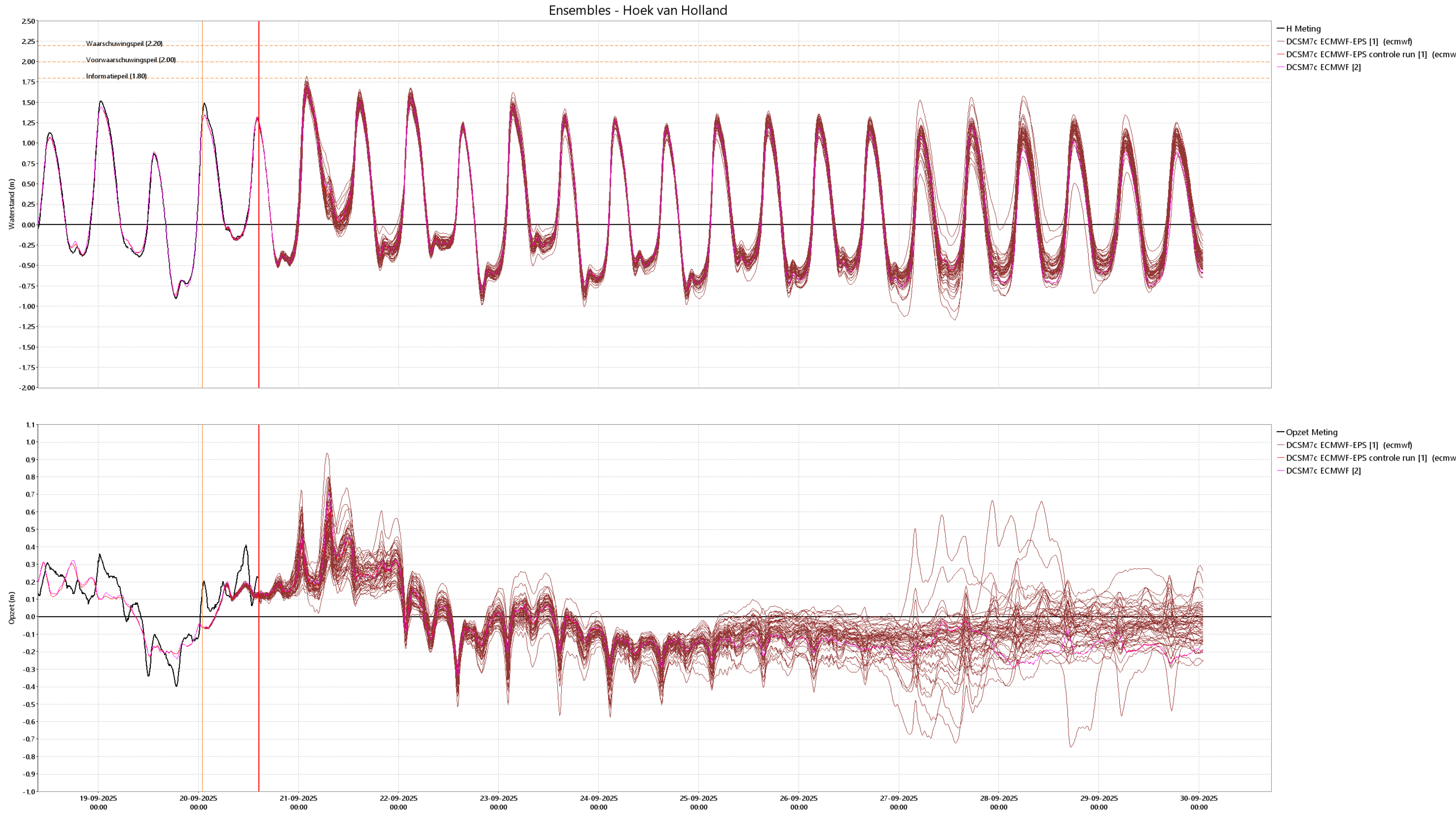
DCSM-FM 100m - network



Model	Resolution	Comp. time (min/day)*	Avg. time step (s)	# nodes
DCSM-FM (0.5nm)	4nm-0.5nm	1.4	119	629,187
DCSM-FM (100m)	4nm-100m	8.7	35	1,602,865
DCSMv6-ZUNOv4	4nm-300m	6.5	60	1,119,106

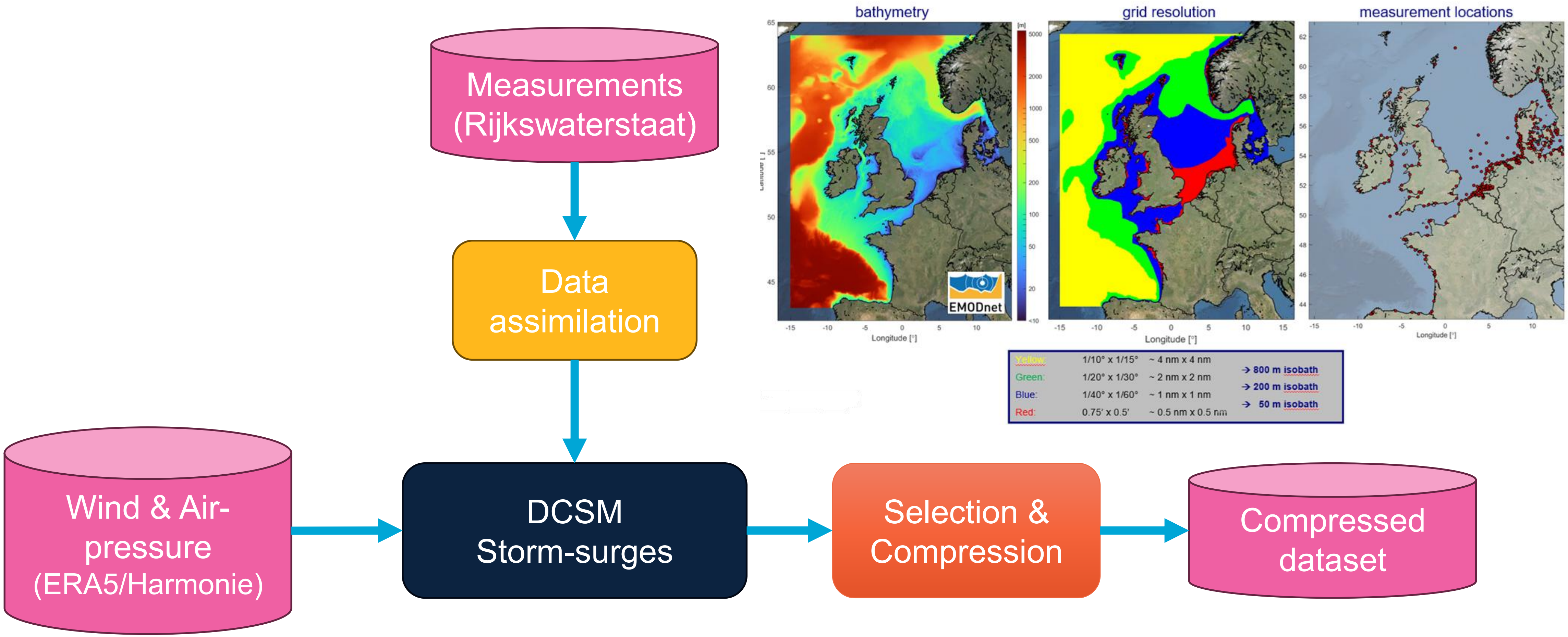
*On 20 CPU cores

Source: presentations by Firmijn Zijl



Ensembles - Hoek van Holland
Waarschuwingspeil (2.20)
Voorwaarschuwingspeil (2.00)
Informatiepeil (1.80)
Waterstand (m)
H Meting
DCSM7c ECMWF-EPS [1] (ecmwf)
DCSM7c ECMWF-EPS controle run [1] (ecmw
DCSM7c ECMWF [2]
Opzet (m)
Opzet Meting
DCSM7c ECMWF-EPS [1] (ecmwf)
DCSM7c ECMWF-EPS controle run [1] (ecmw
DCSM7c ECMWF [2]
19-09-2025 00:00
20-09-2025 00:00
21-09-2025 00:00
22-09-2025 00:00
23-09-2025 00:00
24-09-2025 00:00
25-09-2025 00:00
26-09-2025 00:00
27-09-2025 00:00
28-09-2025 00:00
29-09-2025 00:00
30-09-2025 00:00

Reanalysis training dataset for the North Sea



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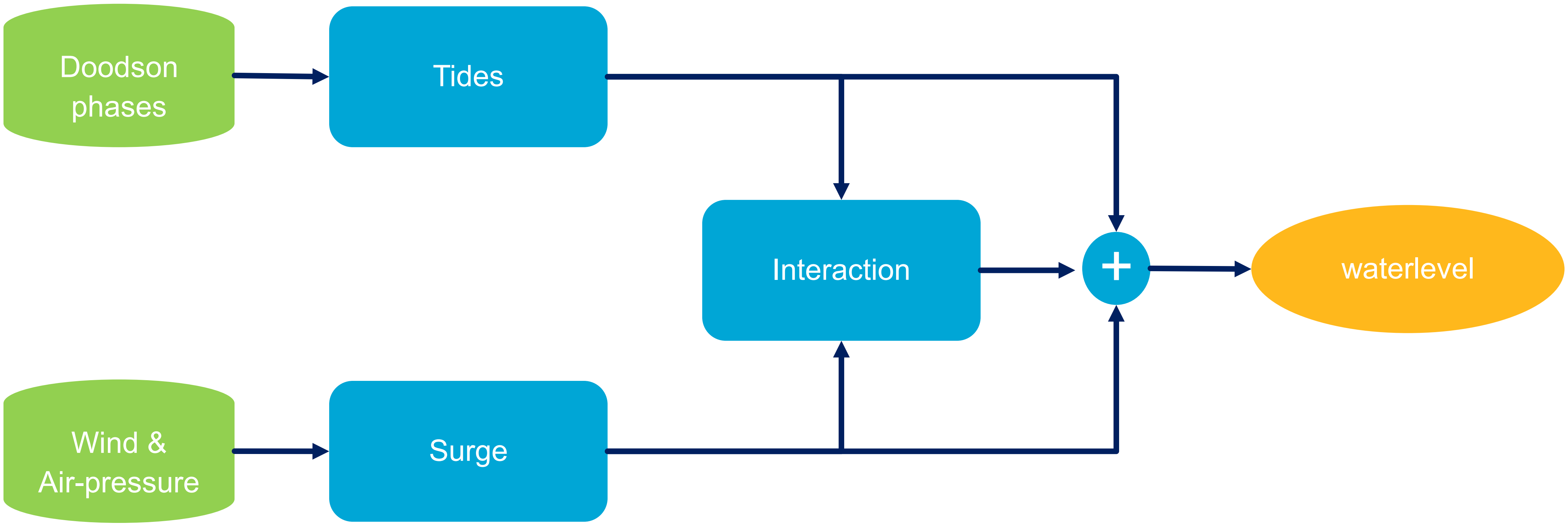
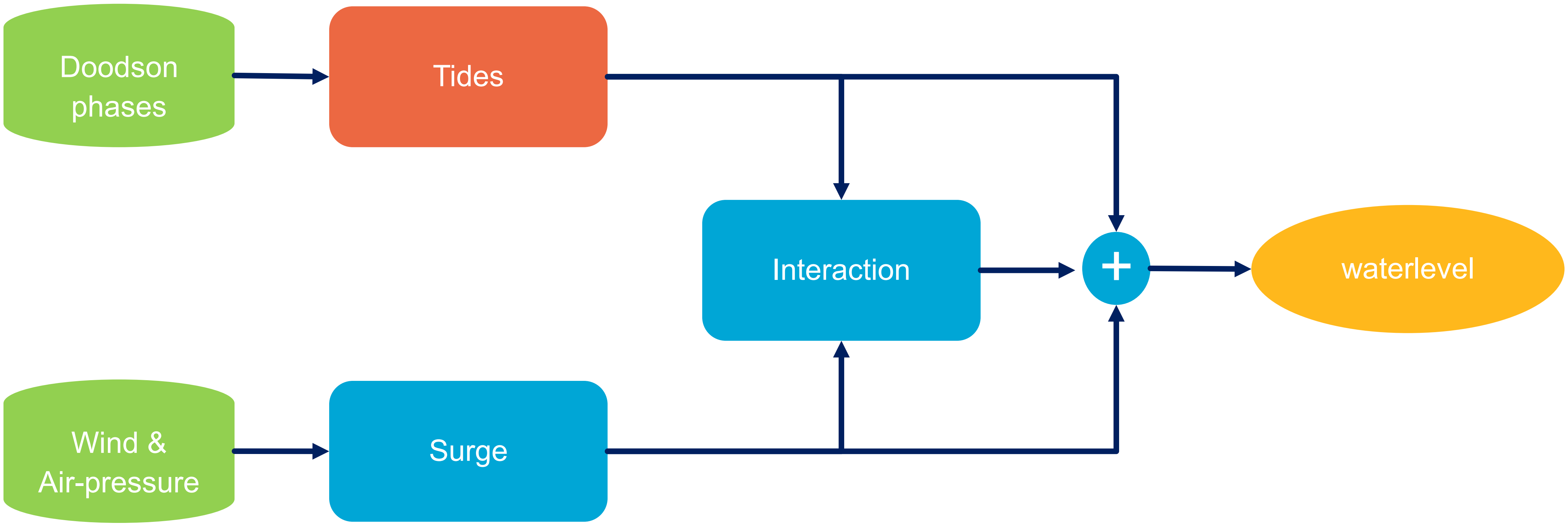
Time-Series ML model

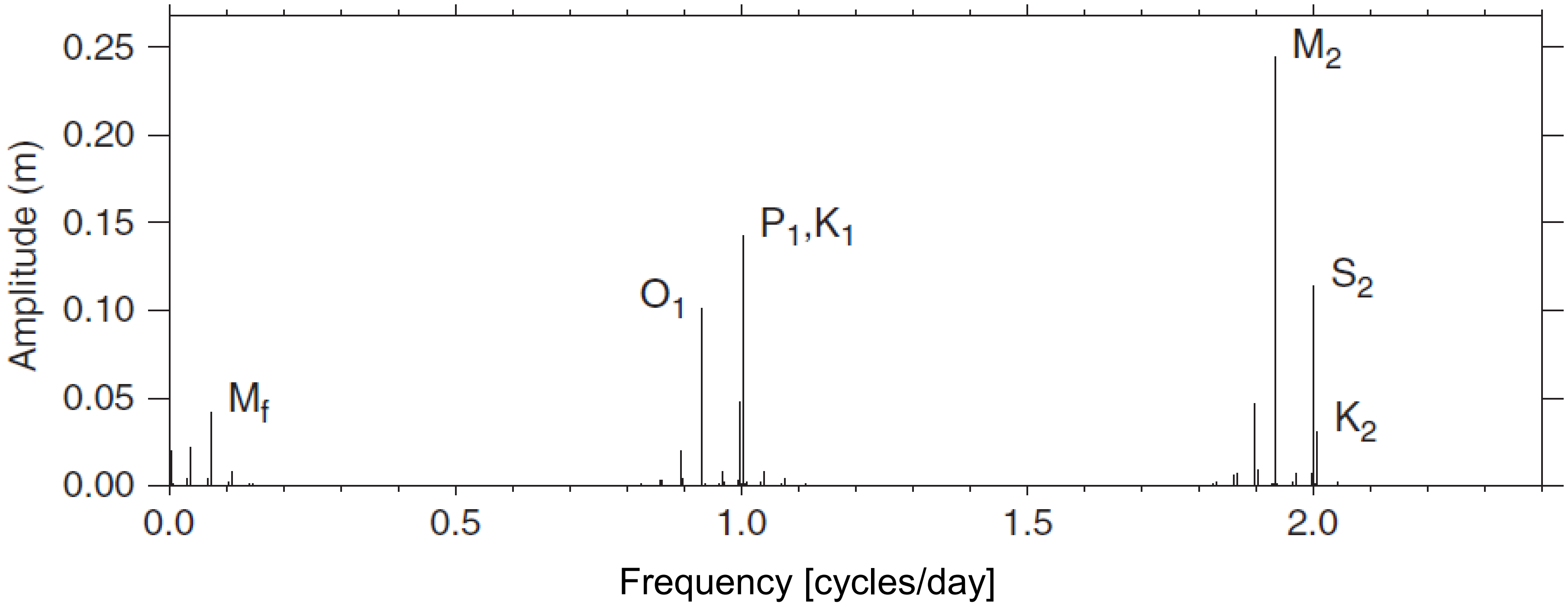
Waterlevel=tides+surge+interaction



Waterlevel=tides+surge+interaction



Tidal frequencies



Doodson phases and tidal analysis

Table 3.2 Basic astronomical periods and frequencies

	Period		Frequency		Angular speed	
			f cycles per mean solar year	σ degrees per mean solar hour	Symbol in rate of radians	Rate of change of
Mean solar day	1.00	mean solar days	1.00	15.0000	ω_0	C_s
Mean lunar day	1.0351	mean solar days	0.9661369	14.4921	ω_1	C_l
Sidereal month	27.3217	mean solar days	0.0366009	0.5490	ω_2	s
Tropical year	365.2422	mean solar days	0.0027379	0.0411	ω_3	h
Moon's perigee	8.85	Julian years	0.0003093	0.0046	ω_4	p
Regression of Moon's nodes	18.61	Julian years	0.0001471	0.0022	ω_5	N
Perihelion	20,942	Julian years	–		ω_6	p'

$$\omega = \sum_{i=1}^{6} d_i \omega_i$$

$$\psi_i = (d_i \omega_i)(t - t_0) + \phi_i$$

Compound tides and over-tides

$$\partial_t h + \partial_x(Hu) + \partial_y(Hv) = 0$$
$$\partial_t(Hu) + \partial_x(Hu^2) + \partial_y(Huv) - fHv + gH\partial_x h + ku|(u,v)| = \tau_x/\rho - H\partial_x p_a$$
$$\partial_t(Hv) + \partial_x(Huv) + \partial_y(Hv^2) + fHu + gH\partial_y h + kv|(u,v| = \tau_y/\rho - H\partial_y p_a$$

Non-linear interactions

$$cos(\alpha)cos(\beta) = \frac{1}{2}(cos(\alpha+\beta) + cos(\alpha-\beta))$$
$$cos(\alpha)sin(\beta) = \frac{1}{2}(sin(\alpha+\beta) - sin(\alpha-\beta))$$

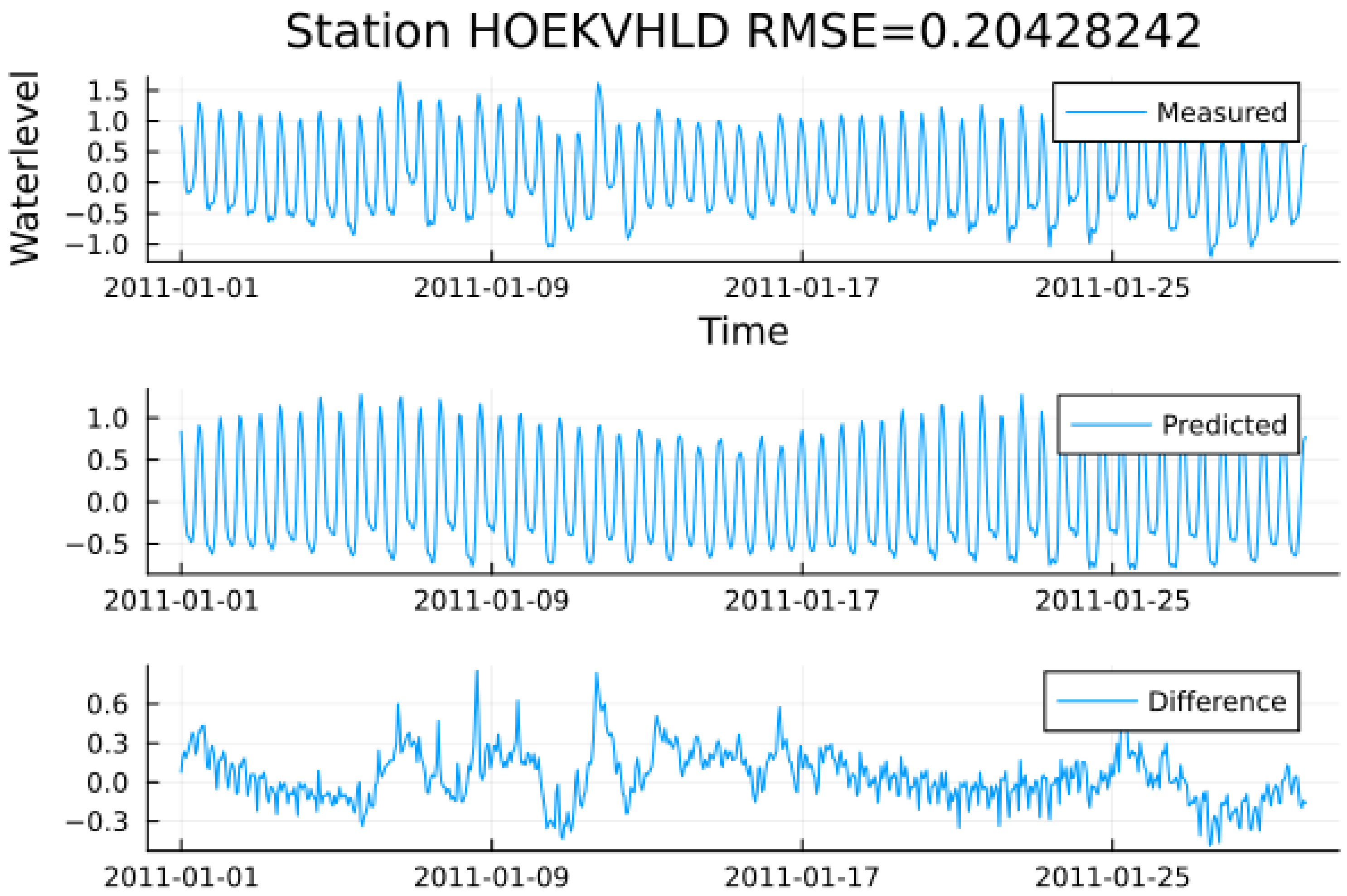
→ Include multiplication in network layer

Example

Name	Doodson	Degrees / hour
M2	2 0 0 0 0 0	28.9841
S2	2 2 -2 0 0 0	30.0000
MS4	4 2 -2 0 0 0	58.9841

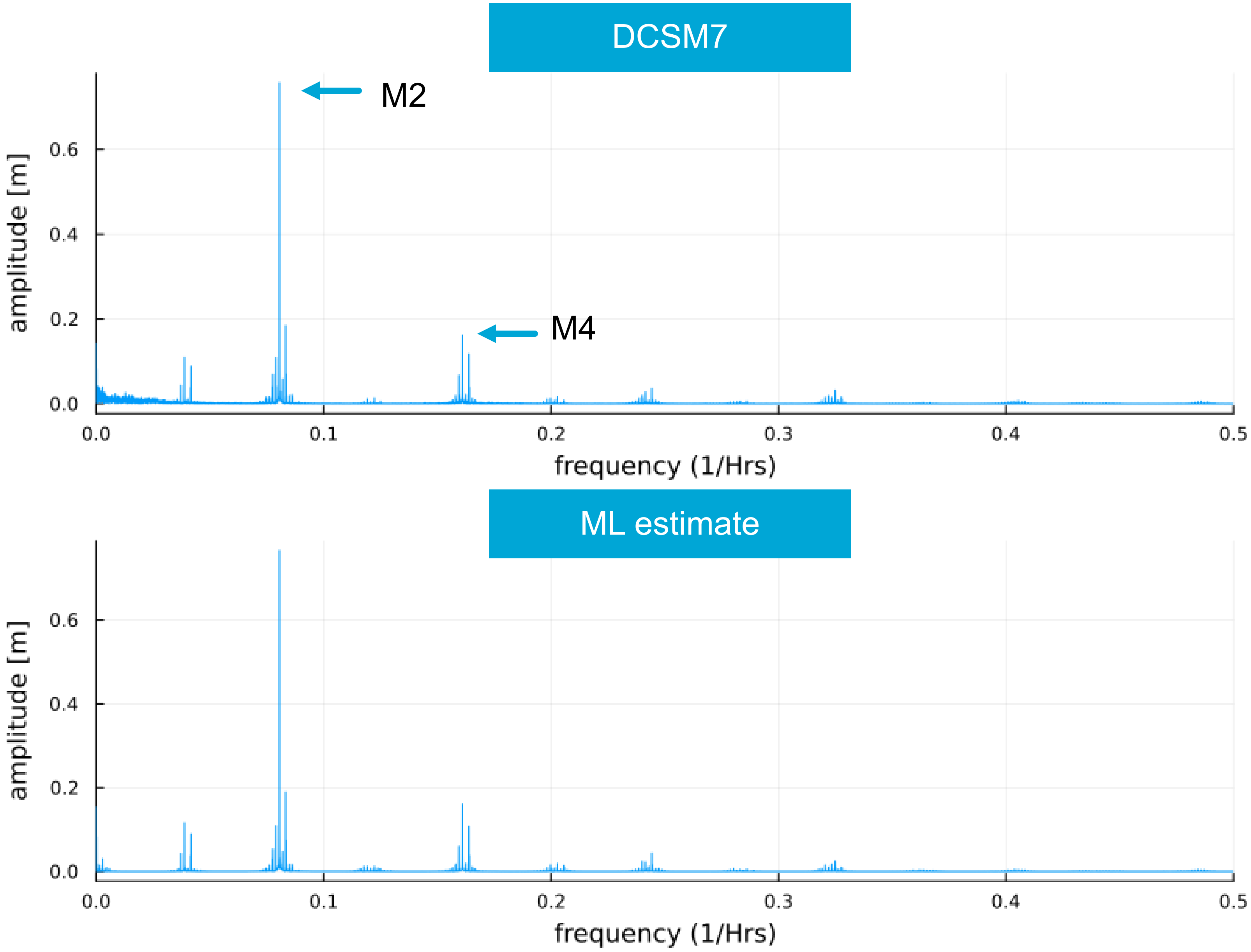
https://iho.int/mtg_docs/com_wg/IHOTC/IHOTC_Misc/TWCWG_Constituent_list.pdf

Tide results test

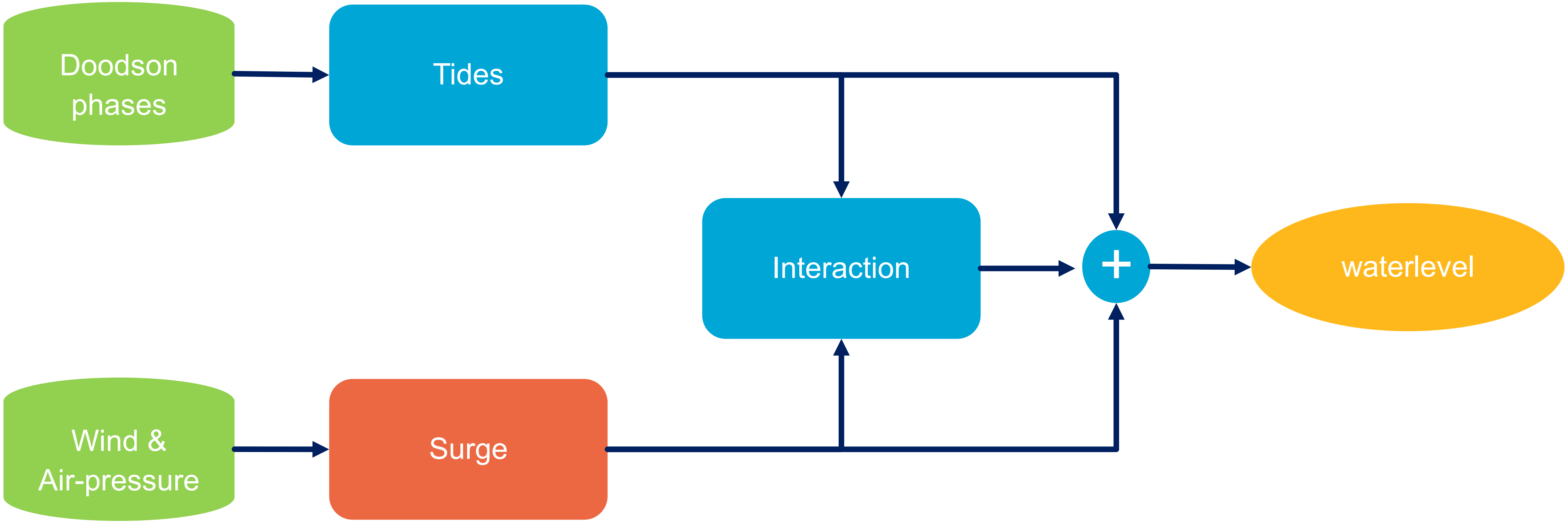


Frequencies

Many tidal frequencies are generated by the network



Waterlevel=tides+surge+interaction



Forcing by wind and air pressure

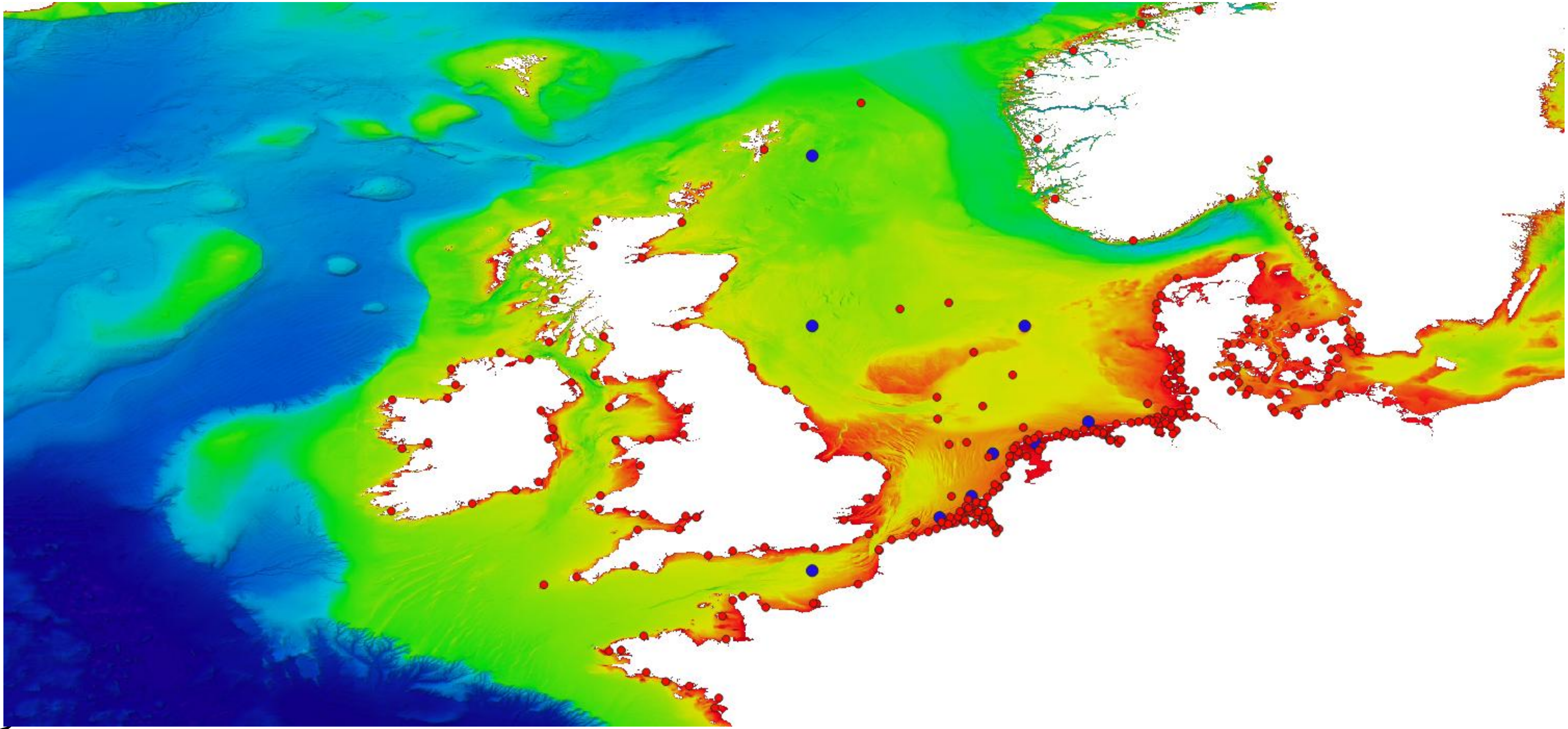
$$\partial_t h + \partial_x(Hu) + \partial_y(Hv) = 0$$

$$\partial_t(Hu) + \partial_x(Hu^2) + \partial_y(Huv) - fHv + gH\partial_x h + ku|(u,v)| = \tau_x/\rho - H\partial_x p_a$$

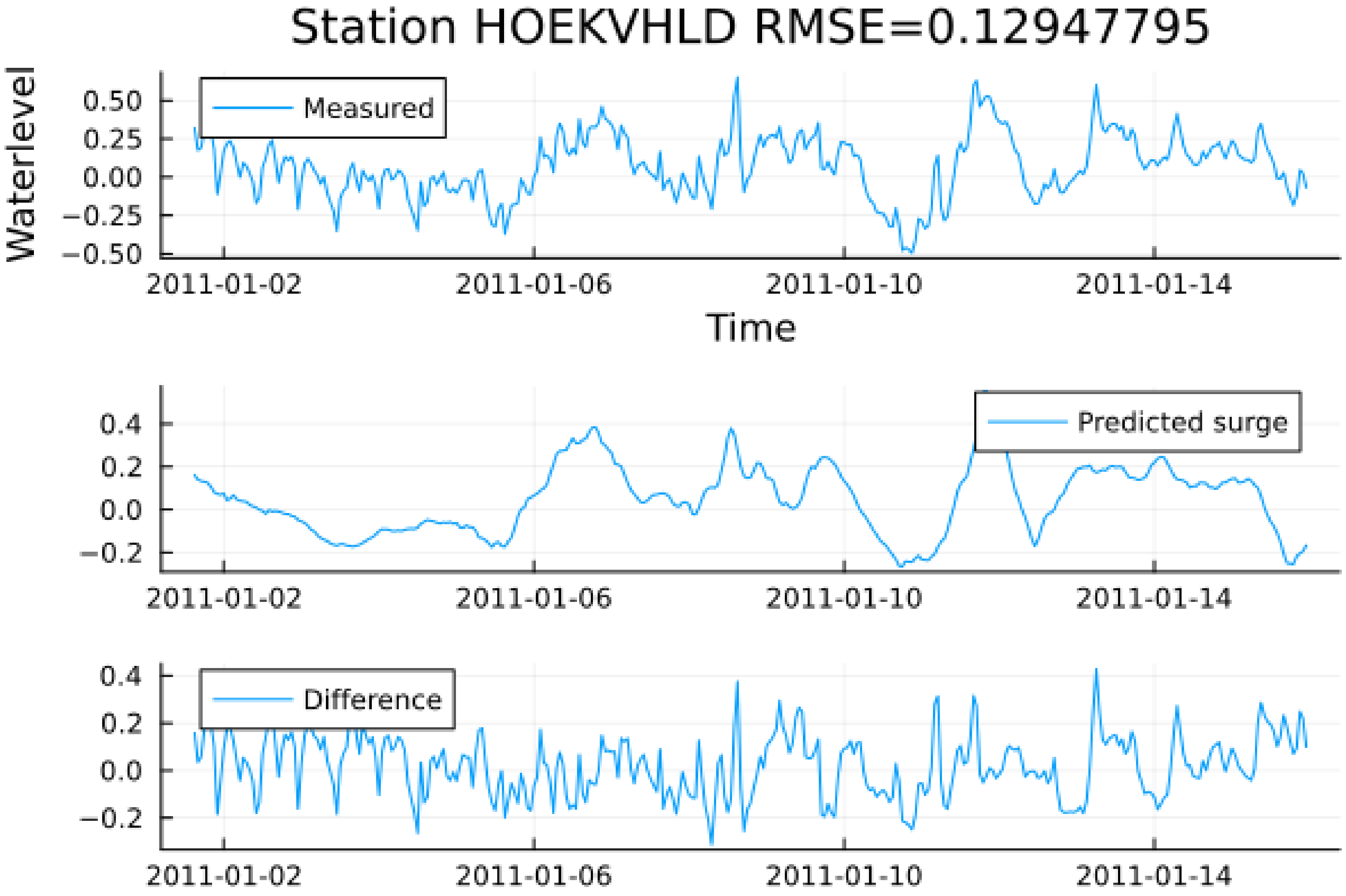
$$\partial_t(Hv) + \partial_x(Huv) + \partial_y(Hv^2) + fHu + gH\partial_y h + kv|(u,v| = \tau_y/\rho - H\partial_y p_a$$

https://en.wikipedia.org/wiki/Shallow_water_equations

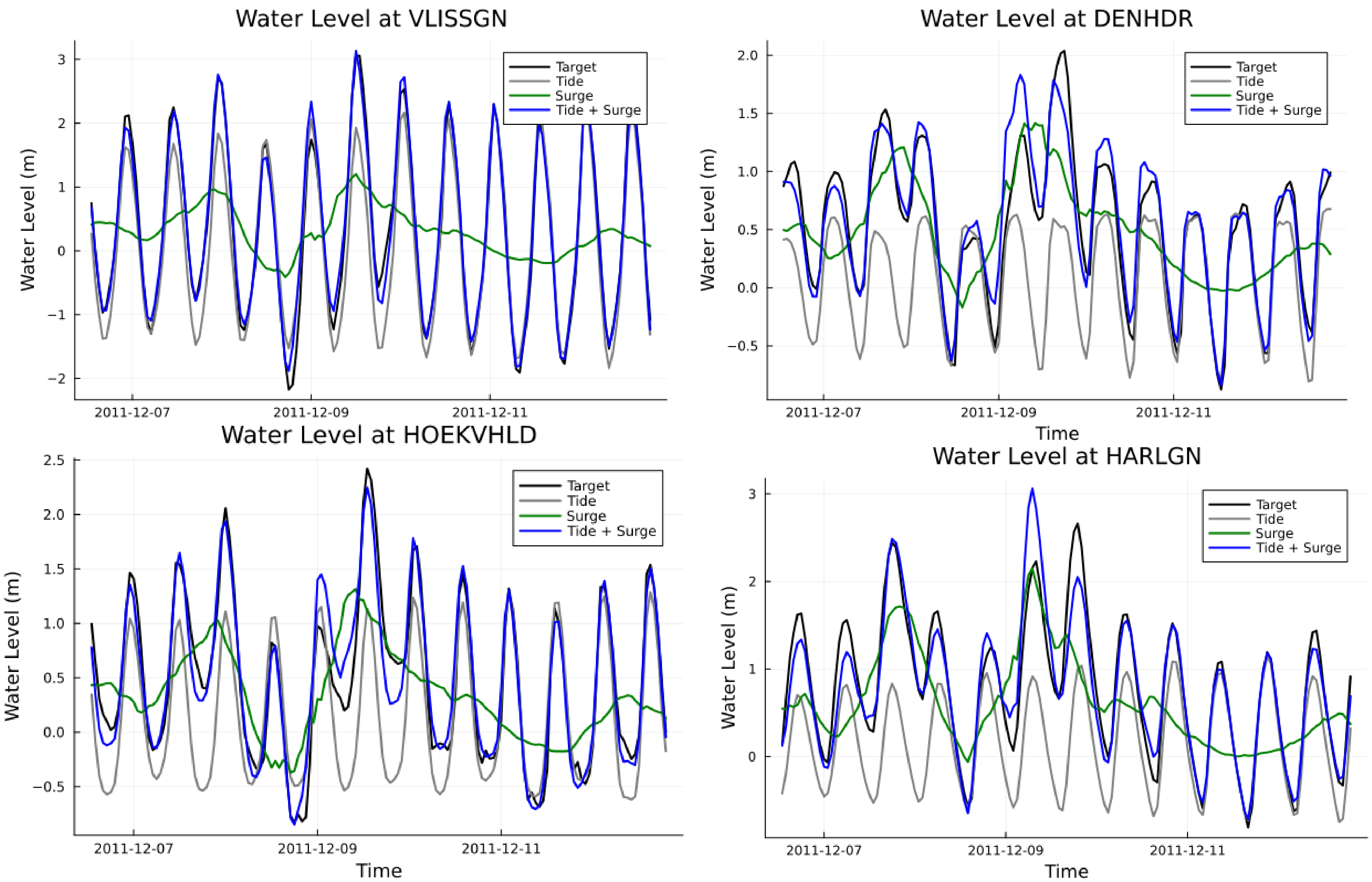
Storm-surge locations



Results testing



Test storm



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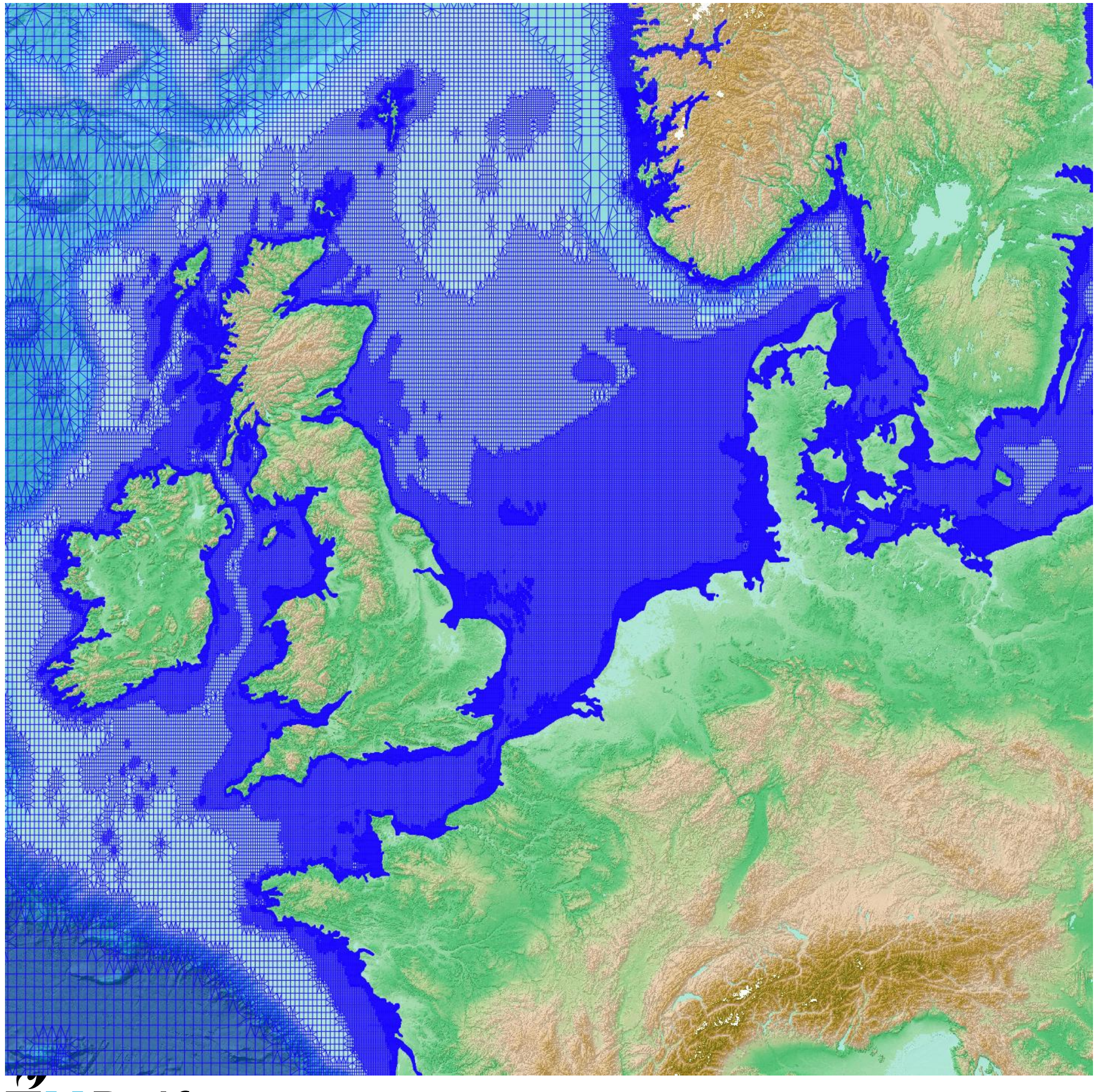
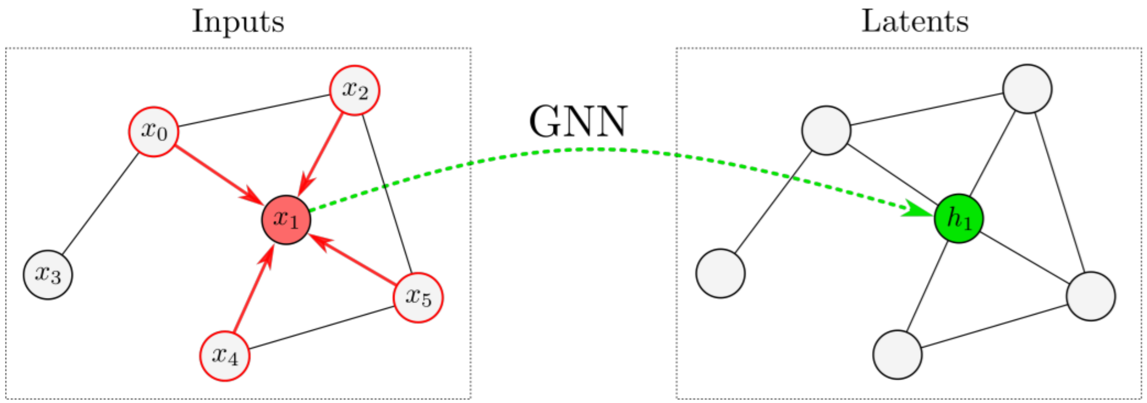
GNN surrogate ML model

A Graph Neural Network for tides & storm-surges



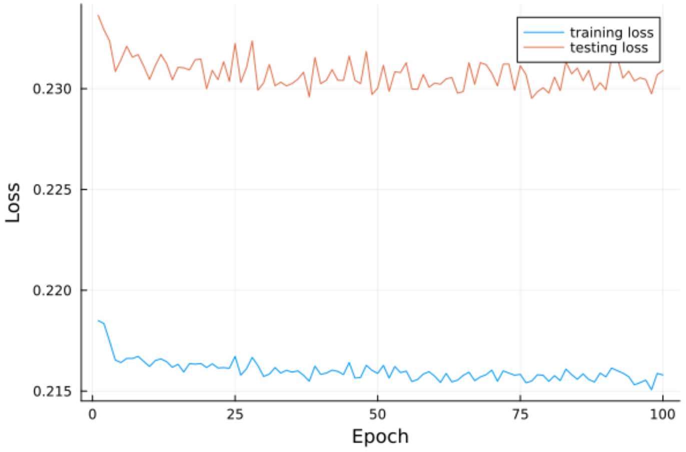


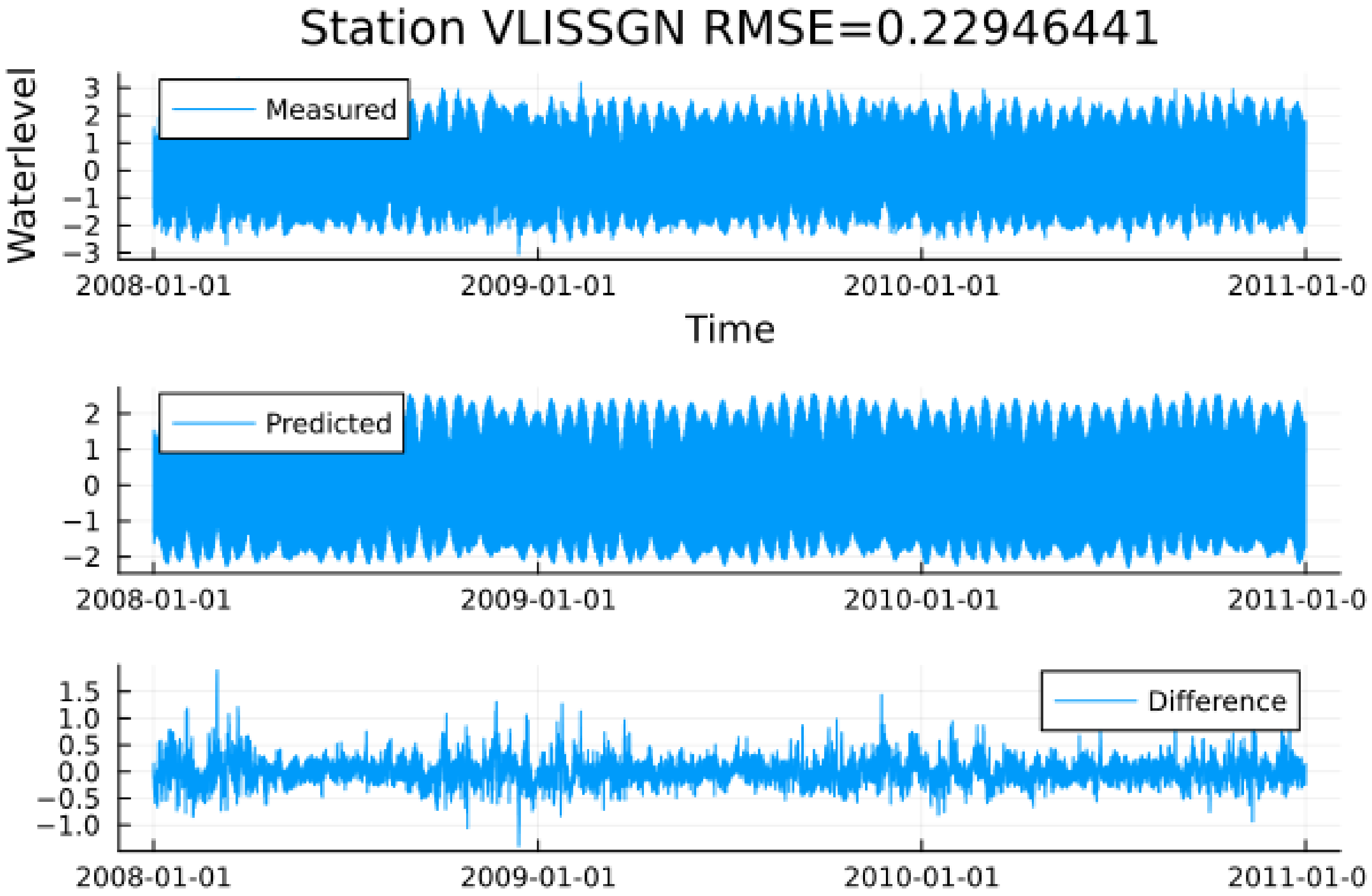
Thanks for your attention.
Questions?

Extra slides for questions

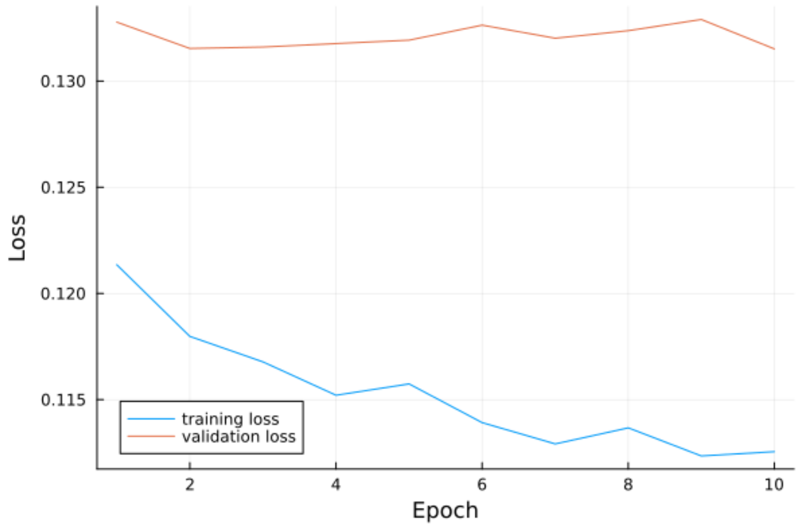
Tide results training

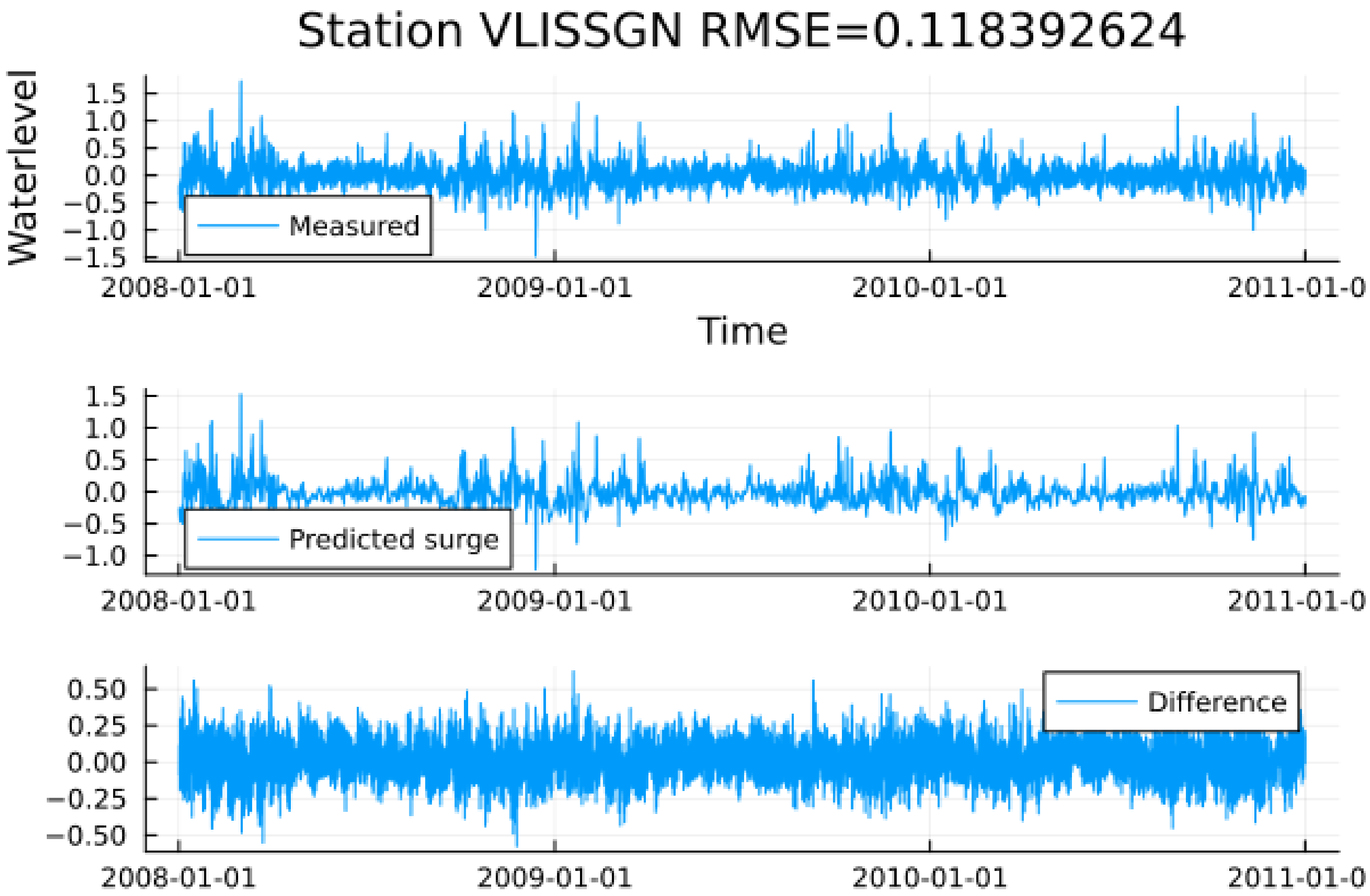
- Training
  - 1-1-2008 – 1-1-2011
  - 317 stations
- Testing
  - 1-1-2011 – 1-1-2012





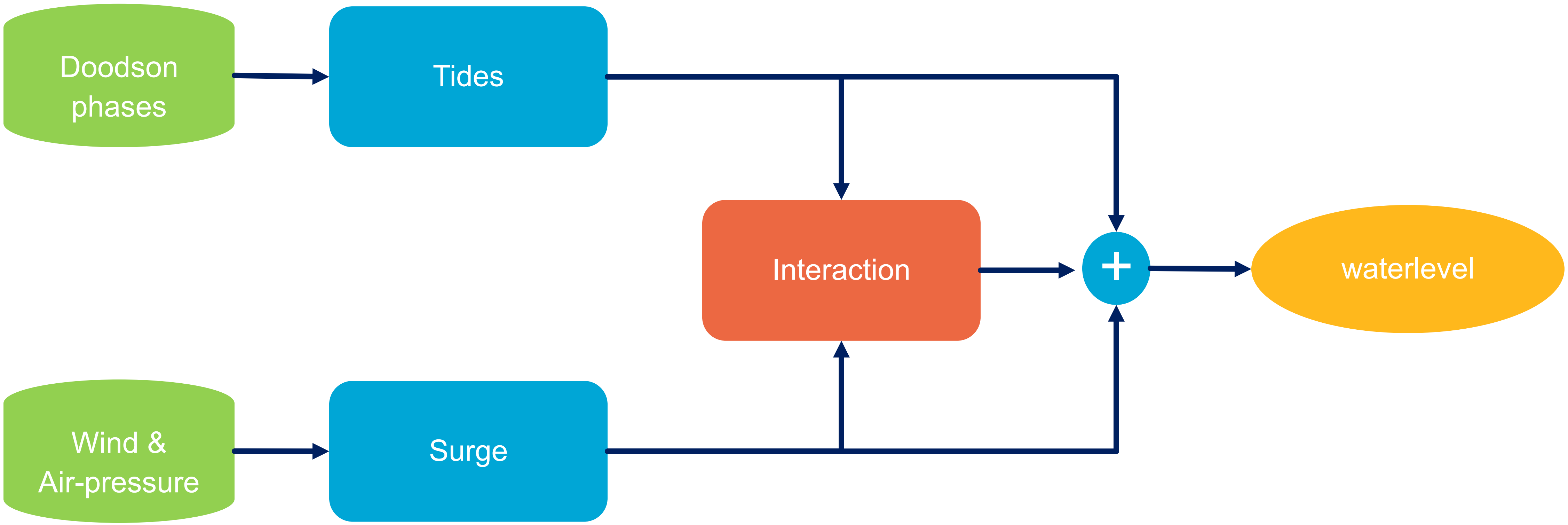
Surge results training



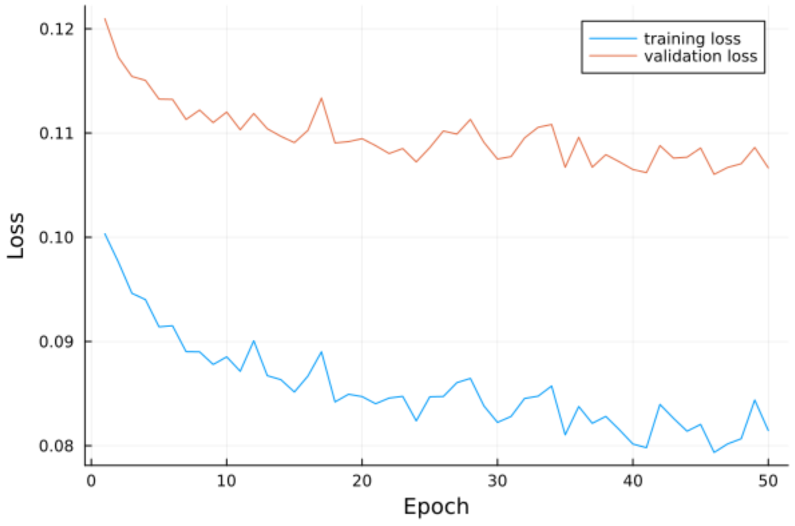


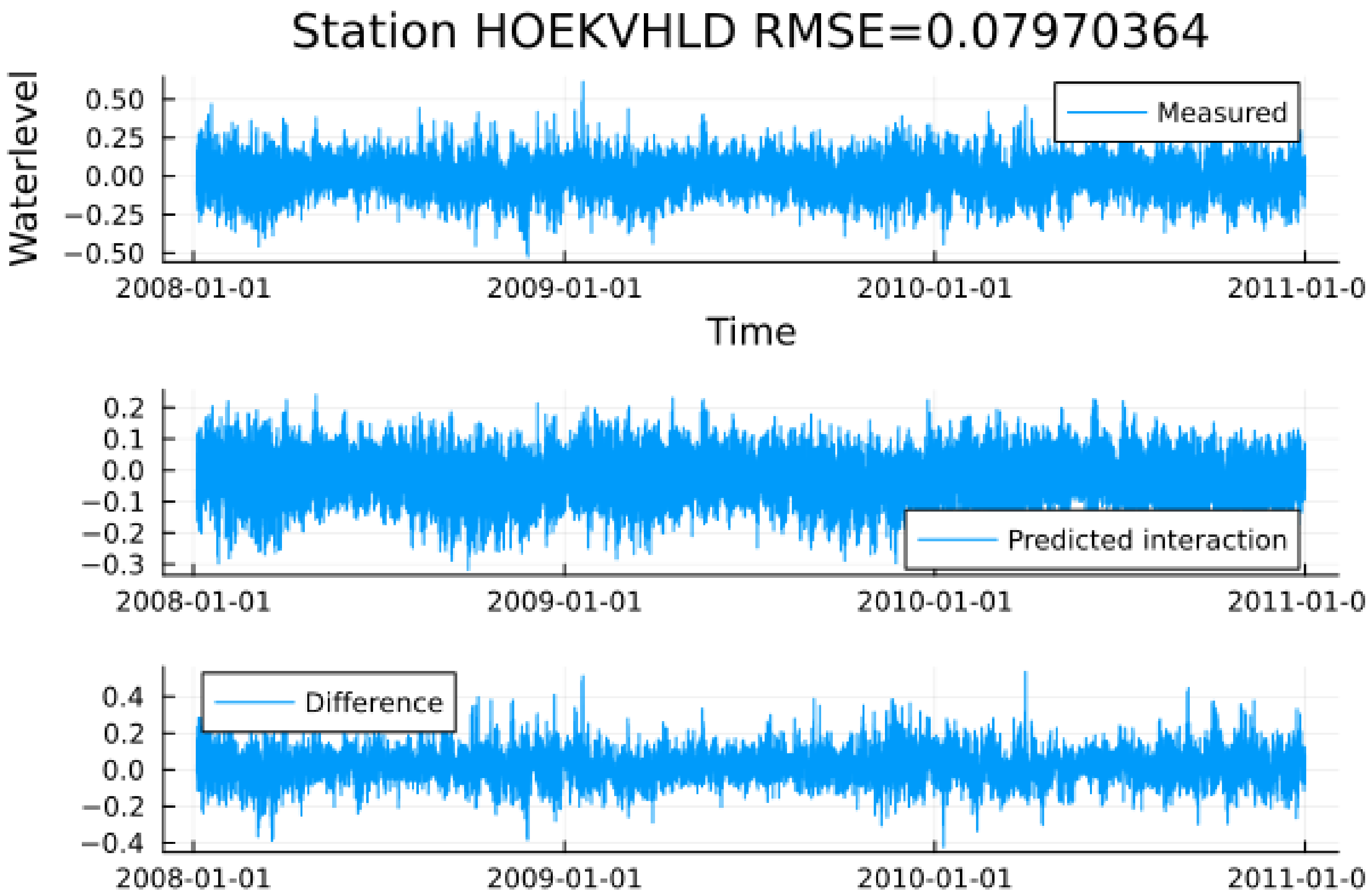
Network inspired by Wavenets (Gulli etal Deep Learning with Tensorflow 2 and Keras)

Waterlevel=tides+surge+interaction



Non-linear interaction training





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Non-linear interaction testing

Station	Signal RMSE	>Tide	>Surge	>Interaction
Vlissingen	132.8	24.0	14.1	11.9
Hoek v Holland	67.4	23.4	11.9	9.8
Den Helder	55.6	24.9	10.4	8.7
Harlingen	70.7	31.6	13.5	10.2
Delfzijl	104.7	31.1	15.3	12.3